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**El Dokor**

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(54) **NEAR TOUCH INTERACTION**  
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(57) **ABSTRACT**  
A near-touch interface is provided that utilizes stereo cameras and a series of targeted structured light tessellations, emanating from the screen as a light source and incident on objects in the field-of-view. After radial distortion from a series of wide-angle lenses is mitigated, a surface-based spatio-temporal stereo algorithm is utilized to estimate initial depth values. Once these values are calculated, a subsequent refinement step may be applied in which light source tessellations are used to flash a structure onto targeted components of the scene, where initial near-interaction disparity values have been calculated. The combination of a spherical stereo algorithm, and smoothing with structured light source tessellations, provides for a very reliable and fast near-field depth engine, and resolves issues that are associated with depth estimates for embedded solutions of this approach.

**Related U.S. Application Data**

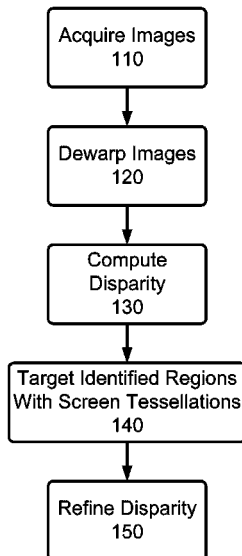
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None  
See application file for complete search history.

**9 Claims, 3 Drawing Sheets**



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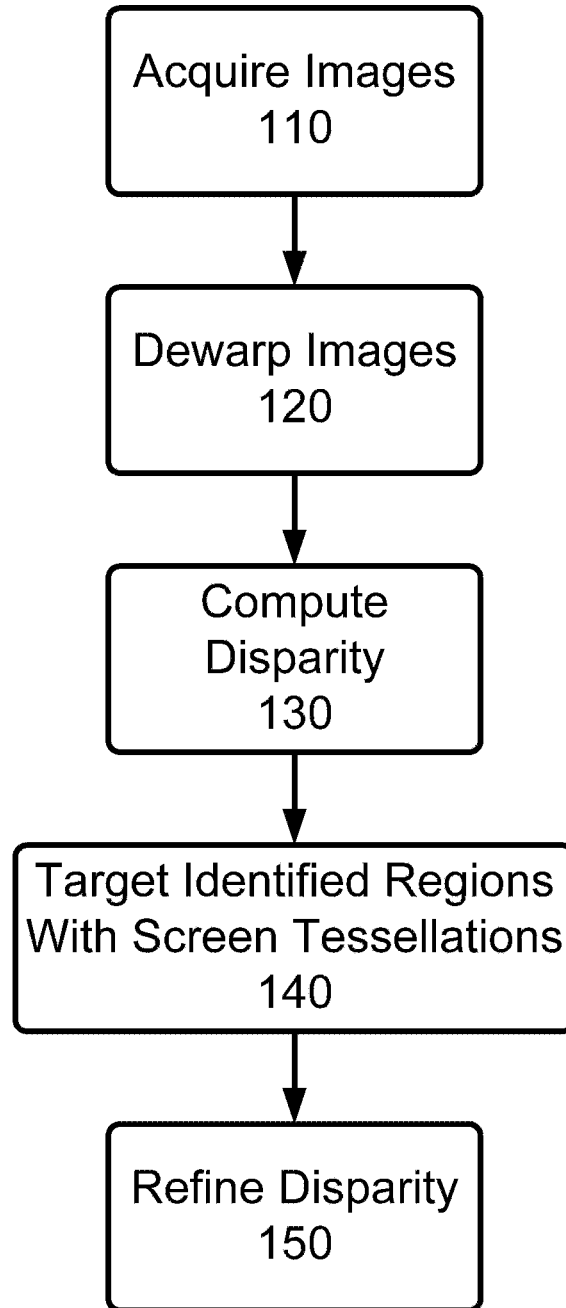


FIGURE 1

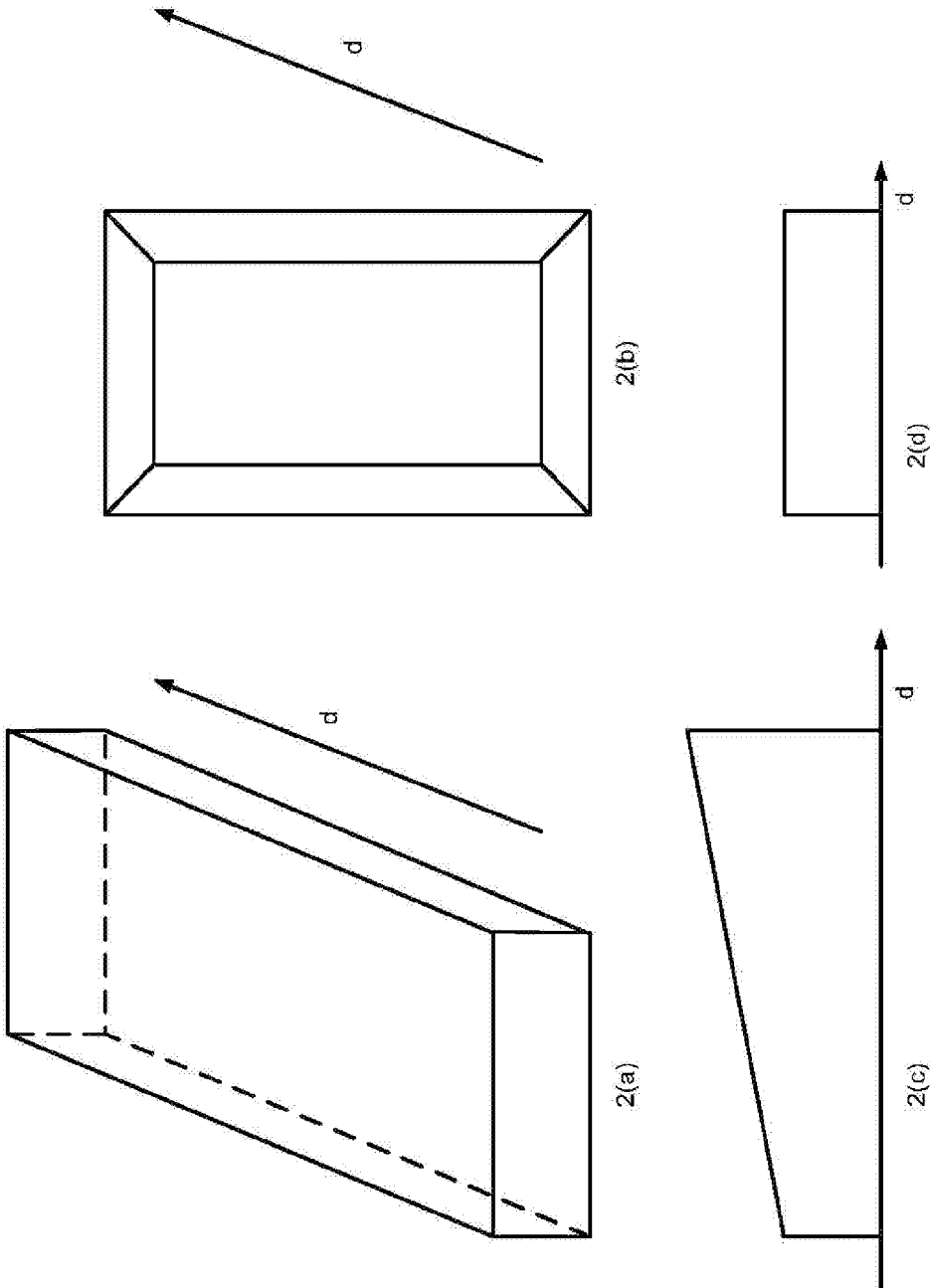


FIGURE 2

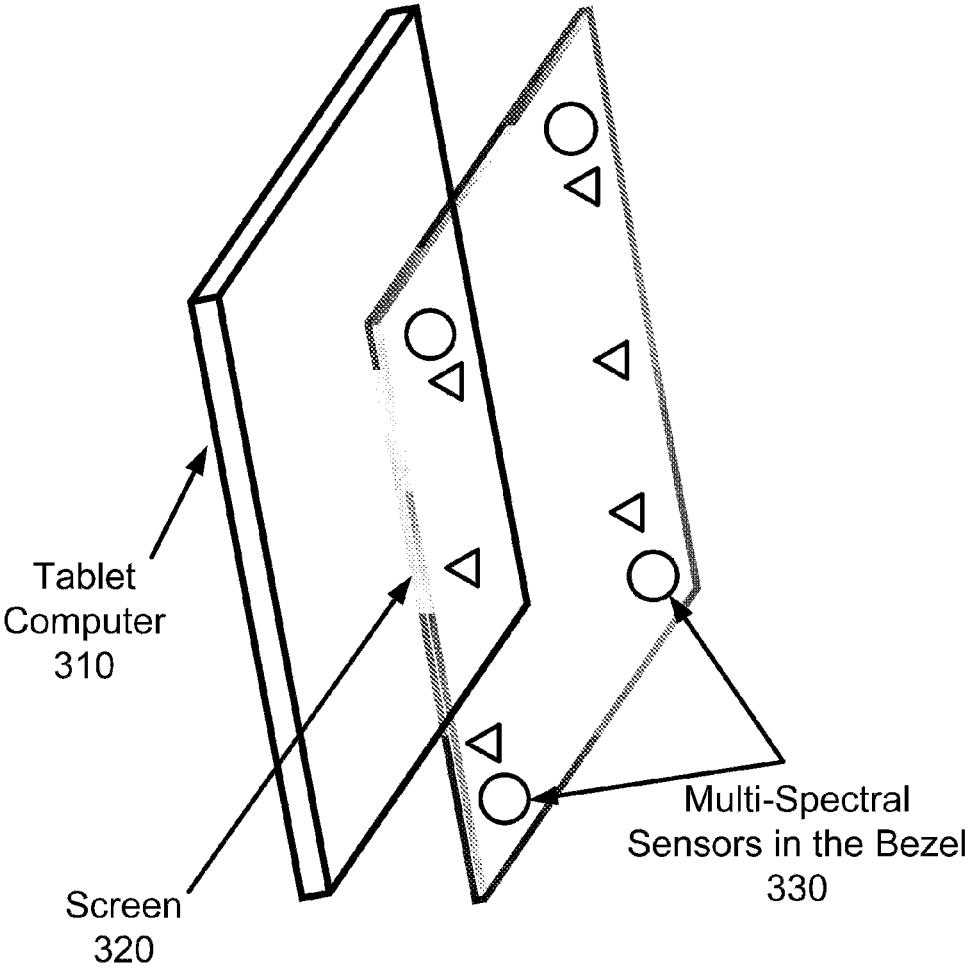


FIGURE 3

## NEAR TOUCH INTERACTION

## CROSS REFERENCE TO RELATED APPLICATIONS

This application is a continuation of U.S. patent application Ser. No. 14/60,032 filed Jan. 19, 2015, titled "Near Touch Interaction with Structured Light" to El Dokor, pending, which is a continuation of U.S. patent application Ser. No. 13/189,517 filed Jul. 24, 2011, titled "Near-Touch Interaction with a Stereo Camera Grid and Structured Tesselations" to El Dokor, now U.S. Pat. No. 8,970,589, which in turn claims the benefit of U.S. Provisional Patent Application Ser. No. 61/441,634 filed Feb. 10, 2011, titled "Near-Touch Interaction with a Stereo Camera Grid and Structured Tesselations" to El Dokor, the contents of each of these applications being incorporated herein by reference.

## BACKGROUND OF THE INVENTION

Multi-touch technology has become a standard modus of interaction with new touch screens. Such screens are becoming more pervasive, making their way into mobile technology and allowing for evolving forms of interaction. Such touch screen technology has enabled a shift in computing into a new brand of devices, including tablet computers, mobile devices and other touch screen supported systems. The problems with various single and multi-touch systems are many. Smudging is the most obvious one, in which the screen becomes unclear from regular usage. Hygiene is another issue in which the screen, especially if used by more than one person, may become unhygienic. Reliability and dependability of the screen are other considerations, along with the price associated with integrating a touch screen into a tablet device. Responsiveness that is associated with multi-touch gestures is another issue, since there exists a significant lag in the operation of the system itself.

A cheaper and more effective solution is to utilize optical sensors embedded in the bezel of the screen at various locations. Systems with sensors arrangements in the bezel are already available on tablets and other systems, and some are being made available in the near future. Optical-based interaction, if successful, is cheaper to install than a touch screen, and provides for a better and more reliable viewing quality. To enable such an optical based interface, depth has to be constructed in an area close to the screen's surface, i.e. a three dimensional representation of any objects positioned close to the screen's surface must be constructed so that movement relative to the screen may be determined. Once depth is calculated, replacing multi-touch gestural events with near-touch events that are emulating the same behavior becomes trivial.

There are no methods available today to reconstruct depth at such a close distance for real-time applications. Some work exists in the literature on spherical stereo, such as that presented in Li, Shigang. "Binocular Spherical Stereo" IEEE Transactions on Intelligent Transportation Systems (IEEE) 9, no. 4 (December 2008): 589-600. however such methods are computationally expensive and lack robustness for them to be applicable to a tablet computer. In accordance with embodiments of the present invention, a different stereo approach, presented in U.S. patent application Ser. No. 13/025,038, filed Feb. 10, 2011 by El Dokor et al., titled "Method and Apparatus for Segmentation of an Image", the contents thereof being incorporated herein by reference, may be employed. A similar dewarping algorithm to that used by Li (noted above) may also be employed as a

preprocessing step to the algorithm. A detailed description of this stereo algorithm has been presented in, for example, the above referenced '038 patent application. Building on the similar concepts of disparity computation with stereo, in accordance with the present invention, a novel approach is utilized for the implementation of near-touch systems.

There are other methods that are known to one of ordinary skill in the art for performing depth computation other than computational stereo. One such method utilizes an active light source with a structured pattern (these methods are sometimes referred to as active stereo). A pattern may be projected onto the field-of-view (FOV) from a light source close to the imager, and then the distance between the individual patterns is calculated. Some examples of this approach include Microsoft's Kinect™ Xbox™ peripheral, and PrimeSense's ASIC+Prime Sensor, as described in Meir Machline, Yoel Arieli Alexander Shpunt and Barak Freedman, "Depth Mapping Using Projected Patterns", May 12, 2010, where various spots of light are utilized for the calculation of a depth map. In addition to the fact that the light source is usually in the infrared range, and requires a significant amount of energy, active stereo suffers from a number of practical and computational drawbacks. For instance, such methods are usually utilized to address depth computation at extremely large distances (relative to the screen, in the context of a few inches), forcing the light source to be very power-consuming and bulky. The data from the depth images have to be evaluated over a number of frames, making the data sluggish and introducing a significant amount of motion blur and computational artifacts that become apparent in performance. Such methods are inappropriate for near-touch interaction.

Therefore, it would be desirable to present a near touch system that overcomes the drawbacks of the prior art.

## SUMMARY OF THE INVENTION

In accordance with various embodiments of the present invention, a method for determining near touch interaction that is significantly more reliable and easy to embed than presently available methods, utilizing depth compute algorithms, is presented. Additionally, the introduction of a light source to smooth disparity computations and the overall generated depth map in targeted regions for further refinement is also presented in accordance with various embodiments of the present invention, and helps to improve the quality and consistency of the depth map.

## Near Touch System

In accordance with embodiments of the present invention a medium of interaction that is to be enabled must first be defined. A near-touch interface may be used to define any interface that can be operated at a distance of roughly 4-14 inches away from a screen. As noted above, there are many technologies that are available today to enable a near-touch system commercially. Some may utilize infrared sensors; others may utilize ultrasound ones. A third category may utilize time-of-flight cameras.

The inventive approach utilizes depth computation, referred to in the above referenced '038 patent application, to produce a depth map. Cameras are preferably utilized with wide-angle lenses, and a dewarping step may be used on the images to remove various warping artifacts and effects that are associated with a wide-angle lens. Dewarping on the data may first be attempted such that two images are input to the system that are mostly free of any lens distortions.



The inventive approach presented in accordance with various embodiments of the present invention may also utilize the screen as a light source, to also minimize the entropy that is associated with a depth estimate, removing the need for further iterating and segmenting larger regions and reducing computational complexity, as described in the above referenced patent application. Additionally, for high-speed LED screens, patterns can be flashed onto the user's hand (or other object being used for near touch) to help improve depth calculations. This is similar to what has been suggested in active stereo methods, where an external IR light source is utilized. Instead, in accordance with the present invention, the screen itself may be utilized as a directed light source, and only targeting specific regions that may require additional information and help in forming an accurate depth map.

Still other objects and advantages of the invention will in part be obvious and will in part be apparent from the specification and drawings.

The invention accordingly comprises the several steps and the relation of one or more of such steps with respect to each of the others, and the apparatus embodying features of construction, combinations of elements and arrangement of parts that are adapted to affect such steps, all as exemplified in the following detailed disclosure, and the scope of the invention will be indicated in the claims.

BRIEF DESCRIPTION OF THE DRAWINGS

For a more complete understanding of the invention, reference is made to the following description and accompanying drawings, in which:

FIG. 1 is a flowchart diagram depicting an overall process flow in accordance with a preferred embodiment of the present invention;

FIG. 2 (including FIGS. 2(a)-(d)) is an example of measurements in accordance with a preferred embodiment of the present invention; and

FIG. 3 is a perspective view of a tablet computing device employing sensors in accordance with a preferred embodiment of the present invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

One or more embodiments of the invention will now be described, making reference to the following drawings in which like reference numbers indicate like structure between the drawings.

An overview of a preferred approach in accordance with an embodiment of the present invention is shown in FIG. 1. As is shown in FIG. 1, at step 110 one or more images are acquired, and then at step 120, these images may be dewarped if desired or determined necessary or advantageous. A disparity is computed at step 130, and at step 140 target regions may be identified and illuminated with screen tessellations. Finally, at step 150, disparity is refined.

In accordance with one or more embodiments of the present invention, wide angle lenses are preferably utilized. Such wide angle lenses allow for a wide field of view to be acquired, allow for the viewing of objects close to the cameras, and thus the display, and also produce a shallow depth of field, thus blurring a background or other objects potentially in the field of view other than the object to be tracked. One or more lenses on the cameras may further be provided to play a role of one or more multiple bandpass

filters to allow and block passage of different frequencies of the light spectrum, as may be determined to be desirable.

The inventive approach allows for a computationally less expensive algorithm and enables a fast iteration with which the initial depth estimate may be further smoothed. In accordance with the invention, an ideal segment,  $s$ , exists in three-dimensional space. The estimated segment,  $\tilde{s}(x, y, \tilde{d})$ , of the ideal segment exists only in one disparity value. Hence, the initial computed disparity represents the orthogonal projection of the segment,  $s$ , onto disparity plane,  $\tilde{d}$ . This is a many-to-one mapping. So, one can define the relationship as:

$$s(x, y, \tilde{d}) = \tilde{s}(x, y, \tilde{d}) + \Psi(x, y) \tag{Equation 1}$$

where  $\Psi$  represents the difference, in disparity between the original segment and its orthogonal projection. Thus,  $\Psi$  is an ordered sequence that has the same dimensions as the given segment, and can be approximated by a mixture of Gaussians. Approximating  $\Psi$  then becomes the real challenge solved in accordance with embodiments of the present invention, to save computation and prevent the need for a further iterative step in the process of formation of the depth map.

Estimating the Disparity Difference  $\Psi$

An efficient means for estimating  $\Psi$  is to compute the disparity associated with an active pattern that is produced from the screen or monitor. That pattern is used to produce a coarse grid of depth values. Some points on this grid do coincide with the overall depth estimate, and some don't.

Define the actual set of all disparities that are associated with a given ideal segment,  $s$ , as:

$D = \{D_1, \dots, D_n\}$ , such that the estimated disparity,  $\tilde{d}$ , is assigned only one value from the set, meaning

$$\tilde{d} \in \{D_1, \dots, D_n\} \tag{Equation 2}$$

Estimating  $\Psi(x, y)$  for the individual pixels,

$$\Psi(x, y) \approx GMM(S_1, S_2, S_3) + \alpha \tag{Equation 3}$$

where  $S_1$ ,  $S_2$ , and  $S_3$  are the three nearest values from the structured light respectively and  $\alpha$  is the associated smoothing factor (as described in Meir Machline, Yoel Arieli Alexander Shpunt and Barak Freedman, "Depth Mapping Using Projected Patterns", May 12, 2010, and GMM represents a mixture of Gaussians. More neighboring values can be included in the estimation. The total number of Gaussian mixtures doesn't necessarily have to be limited to three.

An object that has been estimated at a given disparity is preferably further refined with a coarse disparity estimate within the vicinity of the estimated disparity value, based on the approximation of  $\Psi(x, y)$  that can be obtained from utilizing a structured light source. In a preferred embodiment of the present invention, this structured light source is preferably utilized over only a portion of the object, and in particular, used to aid in refining the depth map for a portion of the object in which such a depth map is difficult to determine, or otherwise is indicative of benefitting from such additional refinement. The light source may further be employed in one or more frames, these frames not necessarily being consecutive. The projections may further be selected in a manner to be shielded from the field of view of a user, or otherwise blocked from view. Such structured light may be further provided as patterns changed at very high speeds, and targeting only portions of the field of view where it is determined such structured light may be helpful in further refining depth estimations. Further, the structured light is preferably adaptive to various environmental condi-

tions, thus becoming brighter when, for example, ambient light is brighter, and becoming less bright when ambient light is less bright. Such patterns may vary in one or more of size, location, orientation or frequency depending on size and depth of the targeted region. These structured light patterns may be further interleaved with actual displayed data so that the structured light may be displayed without being perceived by the user.

The resulting modified segment  $s'(x,y,d')$  represents a smoothed version of the original computed estimate,  $\tilde{s}$ . This smoothed version allows for access to a detailed depth map represented in the data, smoothed over a range of disparities. If a segment is completely parallel to the field-of-view,  $s$  and  $\tilde{s}$  are nearly identical. If the segment is slanted, away or towards the cameras in the field-of-view,  $s$  and  $\tilde{s}$  begin to differ quite significantly. The implications and consequences of this idea will be further considered below.

An easy way to visualize this approach, and to justify the utilization of a lower-resolution coarse depth estimate, to help smooth and improve upon the depth estimate, is to view the projection of each of the two cases (slanted towards and away from the screen) onto the scene, and to evaluate the entropy that is associated with such cases.

FIG. 2 highlights the two cases. In FIG. 2(a), an object is slanted, hence having pixels at a range of disparities. In FIG. 2(b), an object is mostly upright relative to the FOV, hence having most of the pixels at one or two disparity values. Looking at the projections of both objects onto the disparity plane, the uncertainty or entropy shown in FIG. 2(c) is significantly higher than that of FIG. 2(d). Thus, FIG. 2(a) represents an object that is slanted and its associated projection in FIG. 2(c). The error between actual and computed disparity can be quite high. In FIG. 2(b), the object is mostly normal to the field of view and so the error between it and its projection in FIG. 2(d) is significantly lower. In accordance with various embodiments of the invention, this uncertainty in the depth map can be represented and exploited. It can also be mitigated through the utilization of a structured light source projected onto portions of the field-of-view, once such an initial depth map estimate is evaluated.

Disparity Smoothing with Structured Light Tessellations

The generated disparity map represents a surface-based approach to disparity computation. As mentioned in the above referenced '038 patent application, further refinement of the segments can be accomplished by breaking up larger segments both horizontally and vertically. To avoid having to perform this extra computation on a mobile or other system, one approach may be to utilize the screen for displaying a pattern onto the user's hand, and once a hand has been isolated in the FOV, then compute disparity of the pattern.

The smooth disparity estimate represents an integration of the disparity values over a number of rows. From the above referenced '038 patent application, the goal is to have  $s$  and  $\tilde{s}$  overlap nearly entirely at one of the candidate disparity values. The appropriate disparity is estimated as one that maximizes the ratio of the subsequence, relative to its sequence. However, there is a simplifying assumption that may be made in the estimation of disparity, since clustering groups of pixels together fits such pixels planarly, depriving them of any continuous and gradual change. The disparity value that is associated with large objects represents an approximation of the value that is associated with every pixel in such objects. A better approximation of the true value still requires a further step, as mentioned earlier.

Once regions have been extracted from the coarse disparity map, such regions may be depth-computed by projecting a series of coarse tessellations and imposing a smoothing value, to be associated with the actual data. Every tessellation has a series of computed disparity values that are based on a combination of the original disparity estimate as well as the coarse structured light values, presented in Equation 3 above.

It is worth noting that:

$$\Pr(d|S) \geq \Pr(d|\tilde{d}_o), \forall (x',y') \in D \tag{Equation 4}$$

such that  $D$  represents a subset of values of the image, representing the structured set. So, although fewer in number, absent of an iterative step, the structured light depth approximations represent an upper limit on the probability of the computed disparity for the pixels with such values, referenced earlier, provided the computed depth is accurate. However the computed disparities based on the tessellations are too few in number and too coarse, in addition to the number of drawbacks presented earlier in the document. The solution that is being presented here in accordance with an embodiment of the invention preferably including combining both approaches actually leads to an enhanced probability limit. One can observe:

$$\Pr(d|d',S) \geq \Pr(d|\tilde{d}_o), \forall (x,y) \tag{Equation 5}$$

Minimizing Entropy

Hypothetically, for an object that is completely normal to the FOV, the entropy associated with its disparity computation is minimal, since the calculated disparity is based on a computational stereo algorithm that utilizes parallel surfaces to fit segments to their respective disparities. For an object that is slightly tilted in the field of view, the entropy that is associated with computing its disparity is greater, since the object's disparity values are distributed, as was presented in the preceding section, and illustrated in its associated figures.

Another way to view this approach is from an entropy-minimization standpoint. For a given segment  $s$ , with an estimated segment,  $\tilde{s}$ , and associated estimated disparity  $\tilde{d}$ , the more depth values that are associated with the segment, the higher the entropy value that is associated with the segment's estimated disparity  $\tilde{d}$  and vice versa. So, if a segment is perfectly orthogonal to the field-of-view, then the entropy is very close to zero, since the depth estimate is very accurate. However, for slanted segments, the entropy increases significantly.

Since the secondary step that has been described above is performed on the data, depth smoothing is accomplished through an estimate of  $\Psi$ . The different data values,  $\Psi(x,y)$ , of the tessellations, represent points of higher certainty in the disparity estimates. The overall depth map is then recomputed based on the approximated  $\Psi$ . To minimize the entropy of the estimated value, the data,  $d'$ , are smoothed or "influenced" by  $\Psi$  and redistributed.

Define the conditional entropy,  $Q(d|\tilde{d})$ , associated with a depth estimate,  $d'$ , as:

$$Q(d|\tilde{d}) = - \sum_i \Pr(d|\tilde{d}) \cdot \log \Pr(d|\tilde{d}) \tag{Equation 6}$$

Since the conditional probability,  $\Pr(d|\tilde{d})$ , is defined as the probability of getting a disparity  $d$ , when the computed (in this case, observed) disparity is  $\tilde{d}$ , then, one can discern the relationship:

$$Pr(d|\hat{d},S) \approx Pr(d|\hat{d})$$

Equation 7

where S represents the presence of a structure that is associated with the data or a portion of the data, based on the active light source. It is possible to infer the joint conditional entropy, in relation to the conditional entropy associated with the computed depth map:

$$Q(\hat{d},S) \leq Q(d|\hat{d})$$

Equation 8

Entropy minimization becomes very useful in near-touch applications, and highlights how the presence of a directed active stereo tessellation can effectively smooth out the computed and identified depth surfaces, building a more reliable depth map. Having a greater certainty in the data due to the integration of an active light source is a computationally efficient means of identifying “touch points”, regions in the FOV that are close enough to activate the system and replace multi-touch. Instead of the standard light source approach, a defined region with a projected light source becomes a more efficient approach to depth estimation in near-touch applications.

#### Operating Under Various Lighting Conditions

Heterogeneous Sensors to address all Lighting Conditions. —Scene analysis may be classified through three sets of lighting scenarios, without loss of generality:

Indoor lighting: normal lighting conditions in which there is abundant ambient lighting. In such a case, the system may be normally configured to handle very good lighting conditions, and after dewarping, the stereo algorithm should perform very well, with refinement in the form of the structured light tessellations, enabling a smooth depth map.

Outdoor lighting: in such a case, the reader is referred to the above referenced '038 patent application, in which all the different lighting conditions can be accounted for through a very aggressive segmentation/tracking algorithm.

Night-time/NIR conditions: the screen itself may be employed as an active light source. The value associated with the tessellations is increased, while the screen illuminates the FOV and still enables near-touch applications. In an alternative embodiment of the invention, one or more pairs of stereo cameras employed in accordance with various embodiments of the present invention may comprise cameras that cover both a visible and infrared portion of the electromagnetic spectrum. Alternatively, multiple cameras may be employed, together covering such a portion of the spectrum. In this manner, in dim light, infrared information may be relied upon, in part or whole, to aid in determining or refining disparity. If ambient light is determined to be sufficient for visible spectrum viewing, the infrared portion of the data may be disregarded.

To accommodate for the different scenarios, a very good option is to preferably utilize a grid of sensors, as depicted in FIG. 3. As is shown in FIG. 3, a tablet computer or other mobile device **310** is shown with a screen **320** and a sensor grid **330** embedded therein. In such a case, the sensor grid may be sensitive to a broad range of lighting conditions, and the system may seamlessly switch between any different sensors depending on environmental conditions.

#### Advantages of this Approach

This approach, as set forth in the various embodiments of the present invention, has many advantages. The disparity computation step provides a very detailed depth map in the x-y dimension with significant resolution in the z-dimension. The addition of a structured light source emanating from the tablet's screen itself further refines aspects of this

depth map, to better address ambiguous data and provide for further accuracy, and a reduction in the uncertainty that is associated with the data. Typical structured light approaches have proven to be cumbersome, requiring a strong light source, and generating a coarse depth map. Furthermore, there has never been an attempt to utilize a targeted structured light, activating only in specific regions of the field of view, especially ones that are masked away from the user's view, and in which the user's hand is at close proximity to the screen. This approach reduces computational complexity, and improves responsiveness and accuracy of the overall system. Many other advantages may be realized in accordance with various embodiments of the invention.

A new approach for embedded disparity computation for near-touch systems is presented. This approach is efficient and fast, utilizing a combination of a novel stereo algorithm as well as targeted light structures projected on parts of the scene by the screen itself, at distances close to near-touch, in the form of tessellations. The computed tessellations are then utilized to smooth the depth map, and minimize the uncertainty that is associated with the data. The system is very efficient and utilizes a previously developed depth map. The realization of the system is accomplished with a grid of smart sensors that are used, in conjunction with the screen, to address various lighting conditions. Other benefits may be apparent in accordance with application of the present invention. Indeed, while a near-touch system is described, embodiments of the invention may be applied to any gesture-relevant situation (applications) or even a three-dimensional scene reconstruction near the surface of a tablet device.

In accordance with various embodiments of the invention, a number of benefits may be provided, including the following: A new algorithm utilizing both a passive stereo algorithm that is based on our previous work and a structured, targeted tessellation projected on the field-of-view from the screen. An advanced sensor grid to address various lighting conditions that are associated with the system. Identification of “touch points” based on the produced smooth disparity map. Utilization of the disparity map with a multi-touch API or a 3D API.

In accordance with one or more embodiments of the present invention, it is further contemplated that various hardware configurations, including sufficient processing, storage and transmission systems are provided to support the various processors and steps described above. It is further contemplated that such storage and processing elements may be provided locally within a device, or remotely on a cloud or other remote computing or storage environment. In such a situation, communication systems operating over one or more available communication systems may be employed, and also providing for an integrated device capable of combining information from one or more locally and remotely processed, stored or otherwise manipulated information or programming.

Various embodiments of the invention further contemplate a computer program stored on a non-volatile computer medium within the device, or at a remote location. The computer program causing a computer or other processor in the device or remote location to implement an API to aid in performing one or more of the following steps.

- Generating or refining a coarse depth map
- Providing any above-noted control over fine-tuning the light tessellations
- Determining one or more critical data points for acquisition
- Providing control over various screen functionality

Providing integration and replacement of touch-based or multitouch controls

Allowing for integration with one or more artificial intelligence (AI) algorithms for recognition and scene analysis

Still other objects and advantages of the invention will in part be obvious and will in part be apparent from the specification and drawings.

The invention accordingly comprises the several steps and the relation of one or more of such steps with respect to each of the others, and the apparatus embodying features of construction, combinations of elements and arrangement of parts that are adapted to affect such steps, all as exemplified in the following detailed disclosure, and the scope of the invention will be indicated in the claims.

What is claimed:

- 1. A system for determining near touch interaction, comprising:
  - a display for displaying one or more elements thereon; one or more stereo camera pairs positioned adjacent to the display; and
  - a processor for causing the display to flash one or more structured light sequences using the light sources that illuminate the display on a user pointer placed adjacent to the display, determining a depth map in accordance with information acquired by the stereo camera pair,

and if desired, employing the one or more structured light sequences to possibly refine the depth map, wherein the display produces patterns targeting only regions of the field-of view where the depth refinement is determined to be beneficial.

2. The system of claim 1, further comprising one or more appropriate lenses to produce a shallow depth of field highlighting the user pointer closer to the field of view.

3. The system of claim 1, wherein the use of the shallow depth of field results in a blurred background.

4. The system of claim 1, where in the structured light is displayed on only one or more predetermined portions of the display.

5. The system of claim 4, wherein the structured light is directed at a predetermined portion of a field of view of the display.

6. The system of claim 1, wherein the structured light is provided by an image displayed on the display.

7. The system of claim 1, wherein information acquired by the one or more stereo camera pairs is dewarped.

8. The system of claim 1, wherein the processor is located remotely.

9. The system of claim 8, wherein the processor is located in a cloud computing environment.

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